Automated Collection of Soil-Moisture Data with a Low-Cost Microcontroller Circuit

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Abstract. *Monitoring the moisture status of the soil profile is one method used to schedule irrigations. Manual collection of moisture-sensor data, however, can be labor- and time-intensive and cost-prohibitive. Automating the data-collection process allows information to be collected at high frequency with less labor requirements. Reducing the cost of automated measurement equipment would allow more locations to be monitored cost effectively. A low-cost, microcontroller-based datalogger circuit board was designed to continuously monitor and record moisture-sensor data. Circuit boards were fabricated by hand at a cost of $20 in materials, and required 3 h of labor to construct. During two growing seasons, 150 dataloggers were deployed for use in scheduling irrigations. The design, components, programming, operation, and performance of the circuit are described in this article.*

Keywords. *Microcontroller, Microprocessor, Automated data collection, Datalogging, Electronics, Soil moisture, Moisture meter, Sensors.*

Monitoring the moisture status of the soil profile is one method used to schedule irrigations. Sensors are installed in the soil profile at various depths within a crop's root zone and are monitored periodically. As water in the root zone is depleted, sensor readings change. When sensor readings reach a predetermined value, which can vary depending on factors such as crop, soil, weather conditions, and irrigation system characteristics, an irrigation is initiated. Proper timing of irrigations can help ensure that the crop does not become water stressed, and that it is not irrigated before water is needed.

Manual monitoring of sensors in the field can be labor- and time-consuming. For large fields or farming operations, travel time to and from the fields and monitoring locations, and labor requirements for other field operations may result in infrequent visits and sensor readings. Multiple monitoring sites are needed to account for variabilities in crop and field conditions and to implement more efficient, precision irrigation techniques, but may not be practicable. However, frequent monitoring at multiple locations is needed to provide a complete and accurate record of field conditions and to ensure timely response to changing conditions.

Automated collection and recording of field data offers the advantages of frequent measurements and low labor requirements. Installing an electronic monitoring device at each monitoring site allows for continuous, unattended collection of data at frequent intervals. Labor requirements are reduced to periodic visits to the field to download the data. General-purpose dataloggers suitable for use with moisture sensors are available, but are often relatively expensive, and deploying multiple instruments may quickly become cost prohibitive.

A moisture sensor in common use, due to its low cost, ease of installation, and durability, is the Watermark Model 200-SS (Irrometer Co., Riverside, Calif.). The sensor has been in use for many years and has been the subject of many calibration efforts (Thomson and Armstrong, 1987; McCann et al., 1992; Eldredge et al., 1993; Thomson et al., 1996; Shock et al., 1998) and field studies (Yoder et al., 1998; Shock et al., 2002; Leib et al., 2003; Rodrigues de Miranda, 2003; Cardenas-Lailhacar et al., 2005).

The Watermark sensor is commonly read manually with a special handheld meter. The sensor requires an alternating-current excitation for proper sensor operation (Irrometer, 2002; Scanlon et al., 2002). Recently, several manufacturers have begun offering dataloggers either specifically designed or adaptable for use with Watermark moisture sensors. Manufacturers including M.K. Hansen Company (East Wenatchee, Wash.), Spectrum Technologies, Inc. (East Plainfield, Ill.), and Irrometer Co. (Riverside, Calif.) offer dataloggers capable of logging multiple Watermark-sensor measurements. These instruments automatically make and store sensor measurements at varying time intervals, contain other features such as graphical displays and irrigation-system control outputs, and range in price from approximately US$330 to $600 (2005 prices). Other less expensive dataloggers, such as the HOBO devices (Onset Computer Corporation, Bourne, Mass.), do not provide the proper alternating-current excitation, and are less suitable for use with the Watermark sensors.

A research project involving the monitoring of soil-moisture levels in many (>100) small research plots and commercial producers' fields required the deployment of automated monitoring devices. A simple, low-cost device was desired which had the capability to store measurements

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from multiple moisture sensors and one temperature sensor. Other features, such as a real-time graphical display and external control outputs were not needed. The use of the commercially available dataloggers would have been prohibitively expensive for this application, and justified the development of an inexpensive alternative.

A simple datalogger circuit was designed based on an inexpensive programmable microcontroller. A microcontroller, similar to a computer's microprocessor, has internal memory, is capable of storing and executing user-written programs, has a central-processing unit for performing arithmetic and logic functions, and has input/output lines and communications ports for interfacing with external peripherals. A wide variety of microcontrollers are available in varying physical sizes, amounts of memory, speeds, and built-in features, (Cravotta, 2004), and cost as little as US$2 to $3.

One of the primary advantages of a microcontroller is the ability to replace hardware components with software functions. Rather than designing hardware circuit elements to perform specific functions, such as outputting a specified voltage level or measuring an incoming signal voltage or frequency, these functions can be performed by programming the microcontroller. Applying temperature compensation or calibration equations to convert raw sensor signals to meaningful, physical measurements can be accomplished much more simply in software. Changes to the circuit, such as the timing of measurements, the physical units of the sensor measurements, and calibration equations, can be accomplished by reprogramming the microcontroller rather than redesigning or modifying circuit hardware. Additional components, such as non-volatile memory and real-time clocks, can be connected directly to the microcontroller with little or no additional circuitry and controlled through software. Since many functions are accomplished in software, fewer hardware components are required, reducing costs of materials and fabrication. Fewer components can also result in lower power requirements, enabling a device to be battery powered, and space savings, allowing a device to be smaller in physical size.

Objective

The objective of this project was to design and construct a simple and inexpensive circuit to automatically and continuously monitor and record moisture-sensor measurements that was suitable for deployment at many (>100) monitoring locations. This article describes the circuit and its components, microcontroller program, and calibration routine, and discusses the performance of the device in the field.

Materials and Methods

Circuit Design

A circuit was designed to automate soil-moisture sensor measurements. The circuit design was based on a programmable microcontroller, with sensors and peripheral components connected to and controlled by the microcontroller. The main components of the circuit are a microcontroller, real-time clock, nonvolatile memory, multiplexer, sensor excitation subcircuit, and RS232 interface. A brief description of the main components is contained in the following paragraphs, with the programming and circuit operation detailed in following sections. A circuit schematic diagram is shown in figure 1 and a list of circuit components is shown in table 1.

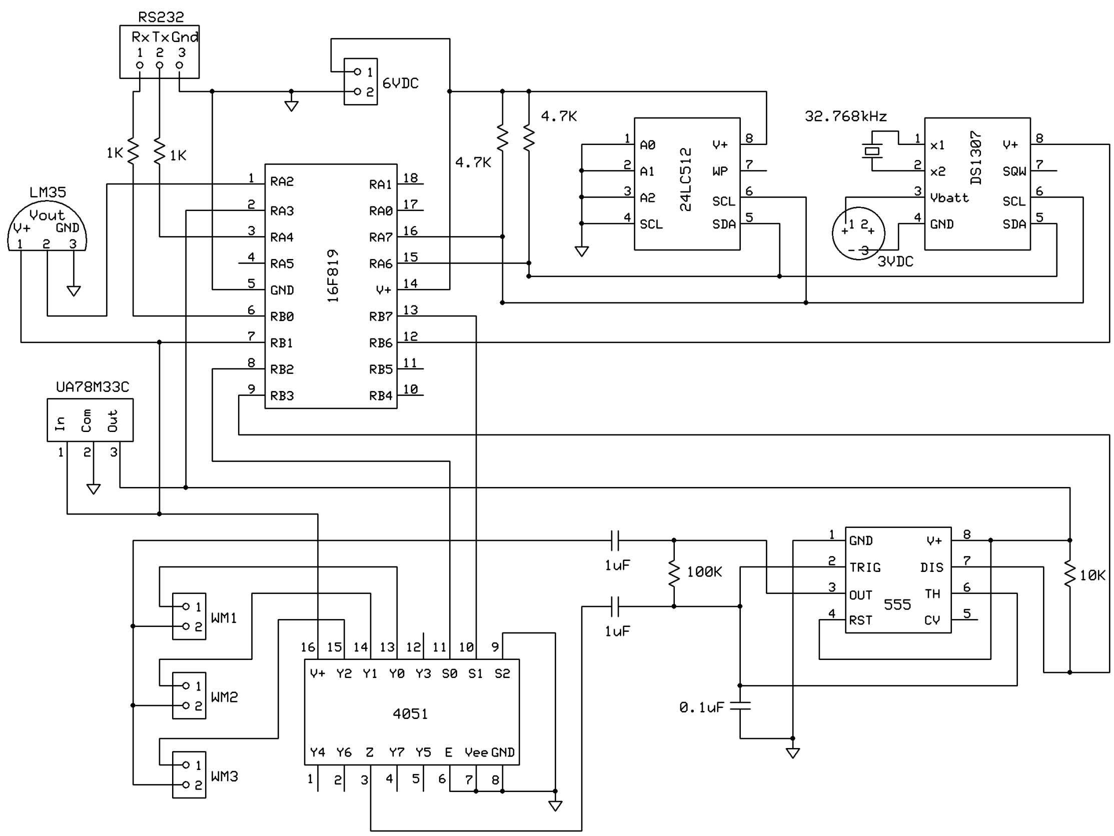

Figure 1. Moisture sensor datalogger circuit schematic.

Table 1. List and estimated costs of moisture sensor datalogger circuit components.

Description	Quantity	Part Number	Manufacturer	Price (US$)[a]
Microcontroller	1	PIC16F819	Microchip Technologies, Inc.	2
Real-time clock	1	DS1307	Dallas Semiconductor	3
Memory	1	24LC512	Microchip Technologies, Inc.	2.50
Multiplexer	1	74HC4051	Phillips Semiconductor	0.50
Temperature sensor	1	LM35	National Semiconductor	1
Timer	1	LMC555CN	National Semiconductor	0.50
Voltage regulator	1	UA78M33C	Texas Instruments	0.50
Clock crystal	1	CFS308	Citizen America Corp.	0.50
Batteries	4	1.5V AA alkaline	Panasonic	1
	1	3V lithium	Panasonic	2
Miscellaneous (resistors, capacitors, headers/pins, board)	3			
Plastic enclosure	1	LP-70F	Polycase	3.50
Approximate total cost of components				20.00

[a] Note: Parts are available from online sources such as Digikey (www.digikey.com), Allied Electronics (www.alliedelec.com), Jameco Electronics (www.jameco.com), and prices shown, current 2005, are approximate.

Soil-Moisture Sensors

The circuit board was designed for use with Watermark Model 200-SS soil-moisture sensors (Irrometer Company, Riverside, Calif.). The Watermark sensors provide an indication of the water potential (or tension) of the soil. These sensors were chosen for their low price (approximately US$25 to 30), availability, and ease of installation. While this circuit was designed for use with this particular sensor, it could easily be adapted for use with other, similar sensors through minor changes to the calibration routine written in the software.

Microcontroller

The PIC16F819 microcontroller from Microchip Technologies, Inc. (Chandler, Ariz.) was selected for this application. The PIC16F819 microcontroller was chosen for its built-in features, which include multiple input/output pins, 10-bit analog-to-digital (A-D) converters, low-power sleep mode, interrupt capability, and ease of programming. The low-power sleep mode allows the microcontroller to be operated on battery power for extended periods of time. The interrupt capability allows an external device, such as a handheld computer, to communicate and interact with the microcontroller. While the native language of the PIC16F819 is assembly language, higher-level languages are available which allow the user to program more comfortably, for example in BASIC or C, and then convert the program to assembly language for download to the microcontroller.

Real-Time Clock

The DS1307 real-time clock from Dallas Semiconductor Corp. (Dallas, Tex.) provides clock and calendar functions. The real-time clock is used to maintain a regular measurement interval, allowing the microcontroller to wake from sleep mode at the proper time, and provides a date and time stamp for data stored to the memory chip. The DS1307 interfaces with the microcontroller via the standard Inter-IC (also referred to as I^2C or I2C) communications protocol (Philips Semiconductors, Netherlands). A 32.768-kHz oscillator provides an accurate timing source, and a dedicated coin-cell battery is connected to the DS1307 to maintain the correct time in case the main circuit battery is disconnected.

Nonvolatile Memory

Data are stored in the Microchip Technologies, Inc. 24LC512 nonvolatile memory chip. The 24LC512 has a storage capacity of 512 kilobits, configured as 65536 8-bit data values. The 8-bit integer values (which can range from 0 to 255) can be stored and accessed randomly by the user. The 24LC512 interfaces with the microcontroller via the Philips I^2C communications protocol.

Multiplexer

A Philips Semiconductor 74HC4051 multiplexer chip gives the circuit the capability to select and monitor multiple sensors. The 74HC4051 is an 8-channel multiplexer, allowing a maximum of eight sensor connections, accessed via three address pins. Since only three moisture-sensor connections were desired, only two address pins were needed in the present application.

Sensor Excitation Subcircuit

The Watermark soil-moisture sensor requires an alternating, rather than a direct, current excitation. The sensor's electrical resistance varies with moisture content, and a constant, direct-current excitation would cause polarization and unstable, erroneous measurements. An excitation circuit was designed using a 555 timer to provide an alternating-current excitation to the sensor and to convert the sensor's resistance to a frequency. The resulting sensor-excitation circuit outputs a signal whose frequency varies with moisture content. This frequency is then measured by the microcontroller, and converted to water potential through a calibration equation.

Serial Interface

Data stored in the memory chip are accessed via a simple RS232 serial interface. Three connections, transmit, receive, and ground, are used. The receive line is connected to the microcontroller's interrupt pin, and the microcontroller is programmed to wake up and enter a data-download routine whenever any signal is detected on this line. The program prompts the user to enter the number of days of data to be downloaded, and the data are sent in ASCII format on the transmit line. The microcontroller is programmed to send data serially with a format of 8 data bits, no stop bits, 9600 baud rate, and no handshaking required. The data can be captured with a common terminal program running on a laptop or handheld computer.

Electrical Power

The circuit was powered using four standard AA-size alkaline batteries. All circuit components, except for the sensor-excitation subcircuit, were able to be powered with an unregulated DC voltage source. A 3.3-V regulator was used to power the sensor-excitation subcircuit and to provide a precise reference voltage for the microcontroller's analog-to-digital converters. With an average current consumption of 80 µA (sleep current plus active circuit current for a 2-h measurement interval), a battery life of approximately two years was estimated.

Temperature Sensor

The circuit was designed to include an optional temperature measurement. An external temperature sensor could be connected to measure the temperature at a depth in the soil profile or of the air inside the crop canopy, for example. The temperature sensor was constructed using an LM35 precision centigrade temperature sensor (National Semiconductor, Santa Clara, Calif.) soldered to a length of three-conductor cable. The LM35 sensor outputs a voltage which is linearly related to temperature and has a manufacturer-stated accuracy of 0.5°C. When measured with one of the microcontroller's built-in 10-bit A-D converters and the circuit's 3.3-V reference voltage, temperatures are measured with a resolution of approximately 0.3°C.

Microcontroller Programming

The PIC16F819 microcontroller was programmed using the PicBasicPro compiler (microEngineering Labs, Inc., Colorado Springs, Colo.). PicBasicPro allows the user to write microcontroller programs in an English-like BASIC language, rather than in the microcontroller's native assembly language. PicBasicPro also simplifies the programming process by accessing many sophisticated microcontroller functions with simple, one-line commands. The user can more easily write programs which utilize the on-board A-D converters, measure frequency, establish serial communications, and transmit commands and data using the I^2C protocol, for example, without having to learn and master the intricacies of these functions.

The PicBasicPro compiler converts a BASIC-language program to an assembly language routine, which is then downloaded to the microcontroller. Downloading is accomplished via a dedicated microcontroller programming device, the EPIC Plus PICmicro Programmer manufactured by microEngineering Labs (Colorado Springs, Colo.). The EPIC programmer is connected via parallel port to a desktop computer running under a Windows environment and operated using microEngineering Labs' proprietary EPICWin software. To program the microcontroller, the microcontroller is physically inserted in the EPIC programmer, the assembly-language routine is downloaded, and the microcontroller is then removed from the programmer and placed in the circuit.

Circuit Operation

A flow-chart outlining the main steps in the program is shown in figure 2, and it is discussed in the following paragraphs.

The microcontroller was programmed to make and store measurements at 2-h intervals. The microcontroller monitors the real-time clock at approximately 2-s intervals by sending a voltage to the DS1307 clock chip via pin RB6 (see fig. 1) and reading the hour, minutes, and seconds. At the beginning of a 2-h measurement interval (hour is divisible by 2, minutes are 0, and seconds are less than 3) the measurement circuit is activated. If these conditions are not met, the voltage to the clock is turned off, and the circuit returns to a low-power sleep mode.

When the measurement period is reached, the microcontroller program activates the remainder of circuit. A voltage is sent via pin RB1 to the LM35 temperature sensor, 74HC4051 multiplexer, and UA78M33C voltage regulator, which in turn powers the LMC555CN timer. The microcontroller uses the month, day, and hour values to determine the beginning memory storage location for the data collected during the current measurement interval. Using date and time information to calculate the storage location ensures that the data are stored consistently and in the proper location , making it easier for the user to access and download data.

A temperature measurement is taken by measuring the voltage output from the LM35 temperature sensor with the A-D converter at pin RA2. The voltage is converted to a temperature using the sensor manufacturer's calibration equation ($T = mV \times 1°C/10\ mV$).

The three soil-moisture sensors are then read one at a time. The microcontroller sets the multiplexer channel using pins RB2 and RB7, and connects the first moisture sensor to the sensor-excitation subcircuit. The sensor's internal resistance, which is dependent on the moisture level of the soil, causes the excitation subcircuit to output a signal whose frequency is dependant on sensor resistance. The microcontroller measures the frequency via pin RB3 and converts frequency to water-potential using a calibration equation. The process is repeated for the second and third sensors.

Upon completion of all sensor measurements, date, time, temperature, and moisture-sensor data are stored to the memory chip. The memory chip has sufficient capacity to store an entire year (12 months) of data, at 2-h intervals, without overwriting or losing any data.

The microcontroller program includes a hardware interrupt routine which allows the user to communicate with the circuit board via laptop or handheld computer. This routine is used to set the time on the real-time clock, give each circuit a unique identification number, and download data. To activate the routine, a cable is connected from the computer's serial port to the circuit board's RS232 connection, and a terminal program on the computer is run. The interrupt routine is activated when any computer key is pressed, and a menu of options is displayed (see flowchart in fig. 2). The user selects an option and is prompted to enter the appropriate information.

Downloading Data

Data were downloaded periodically by visiting each sensor site in the field and connecting a portable computer. A Palm Model IIIxe handheld computer (Palm, Inc., Sunnyvale, Calif.) was used to communicate with the microcontrol-

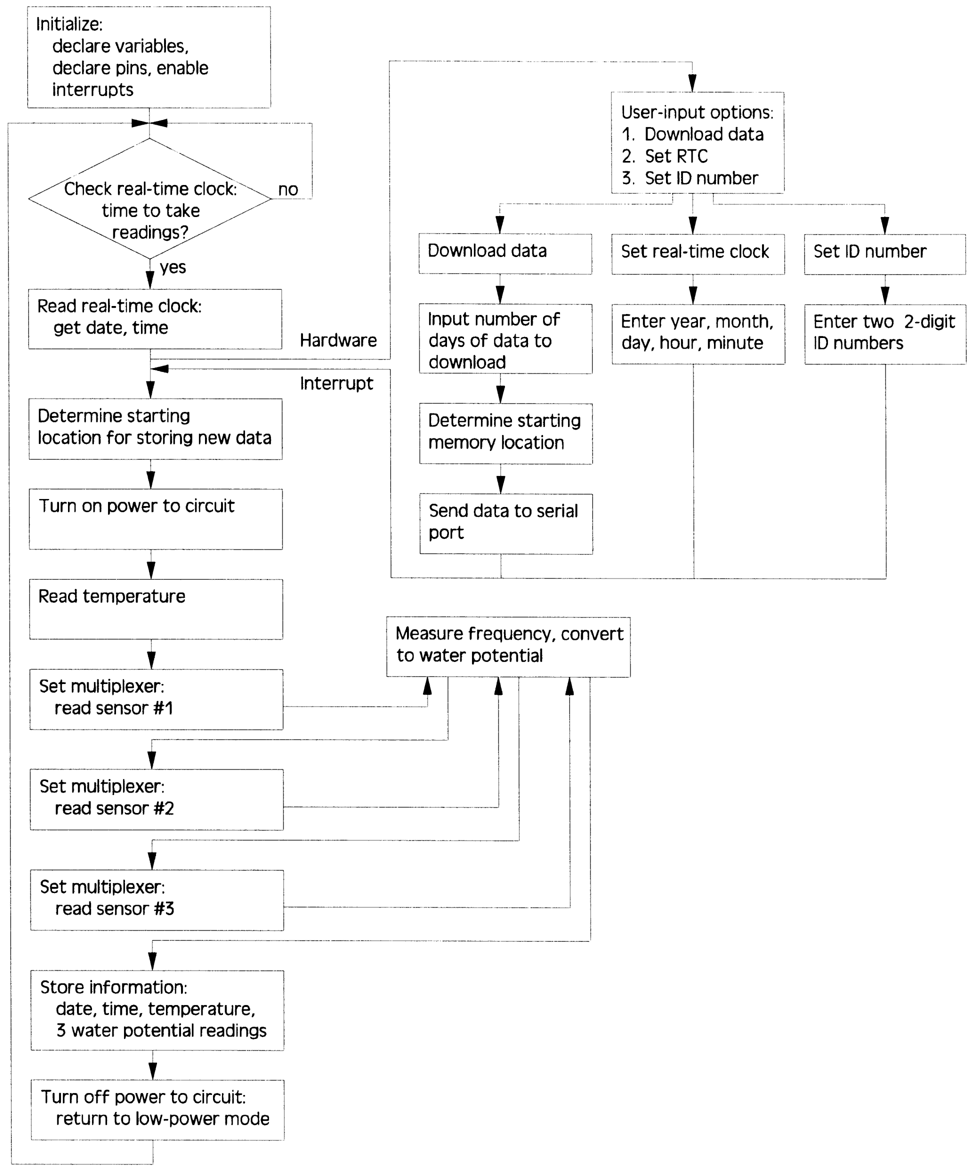

Figure 2. Microcontroller program flowchart.

ler and receive and store the resulting data stream. A standard Palm Hotsync serial cable was modified to plug into the circuit board. A serial terminal program, Ptelnet (Migueletto de Andrade, 2003), was installed on the Palm computer and enabled communication with the microcontroller for data transfer and storage. Data stored on the Palm computer, in ASCII text format, were then transferred to a desktop computer during a Palm Hotsync operation for later graphing and analysis.

Water-Potential Calibration

Watermark sensors are often read manually with a handheld meter, Model 30 KTCD-NL Watermark Meter (Irrometer Co., Riverside, Calif.). The meter measures the sensor's internal resistance and contains a calibration routine to convert the measured resistance to a water potential. The calibration routine consists of two different resistance-to-water potential calibration equations, one for potentials in the range of 0 to 10 kPa, and a second for the range of 11 to 200 kPa (Eldredge et al, 1993; Shock et al., 1998).

The microcontroller circuit, in contrast, does not measure the sensor's internal resistance directly. The sensor resistance forms part of an oscillator circuit which outputs an alternating signal whose frequency is a function of resistance. As the soil and sensor dry, the soil-water potential decreases (becomes more negative) and the sensor's internal resistance increases. The increasing resistance causes the frequency of the output signal to decrease. The microcontroller program uses a built-in PicBasicPro routine (PULSIN) to measure the frequency of the alternating signal in terms of pulsewidth. As the signal alternates between periods of high and low voltage levels, the PULSIN routine measures the length of time, or duration, in microseconds (μs), of the high-voltage state. This pulsewidth measurement is then used to calculate a water potential via a calibration routine.

The water-potential calibration routine was developed for the microcontroller using fixed-value resistors and a Watermark Meter. Two series of resistors were chosen, one series to span the range of water potentials from 0 to 10 kPa, and a second series to span the range of 11 to 200 kPa, to match the calibration routine built into the Watermark Meter. Each resistor was connected in turn to the Watermark Meter, and the corresponding water-potential value, in kPa, displayed by the meter was recorded. Each resistor was then connected to the microcontroller circuit, and the corresponding pulsewidth value, in µs, was recorded. This was repeated for each of the 150 circuit boards that were fabricated. The resistor values and corresponding meter and microcontroller-circuit readings are shown in table 2.

Water-potential values were then plotted as a function of pulsewidth. Empirical equations were fit to the data, and second-order polynomial equations were found to fit the data well. Calibration data and the resulting polynomial equations for the microcontroller calibration routine are shown in figures 3 and 4.

The resulting calibration equations are as follows:

$$WP = (7 \times pw - 860) \times pw/100000, \text{ for } 0\ \mu s < pw < 450\ \mu s$$

$$r^2 = 0.975, \text{ standard error} = 0.5 \text{ kPa}$$

and

$$WP = ((16 \times pw + 115600) \times pw) / 10000000 + 5, \text{ for } 450\ \mu s \leq pw < 8000\ \mu s$$

$$r^2 = 0.998, \text{ standard error} = 2.5 \text{ kPa}$$

where
WP = water potential, kPa
pw = pulsewidth, µs.

The range in water potential values obtained with the calibration equations for each of the calibration resistors is shown in table 2. Absolute errors in calculated water potential values ranged from 0 to ±10 kPa (2- to 191-kPa resistor).

Results

In spring 2004, 60 circuit boards were fabricated and deployed in various research plots at the Jamie Whitten Delta States Research Center (Stoneville, Miss.). In spring 2005, an additional 90 circuit boards were fabricated and deployed. The cost of materials to construct each circuit board, including microcontroller and other electronic chips and components, circuit board, and batteries, was approximately $US20. Each board required three hours labor to construct, program, and verify proper operation prior to deployment in the field. While the cost of materials and labor can vary greatly depending on country and location, a labor cost of US$13 per hour (average wage for electrical and electronic equipment assemblers, U.S. Bureau of Labor Statistics, 2004) would result in a total cost of US$59 per unit.

The circuit boards were deployed at locations where moisture sensors had previously been installed. At each location, three sensors had been installed at varying depths below the soil surface, and had been monitored manually in the past. The circuit boards were installed to automate the data-collection process and to provide information for scheduling irrigations of cotton, corn, and soybean crops.

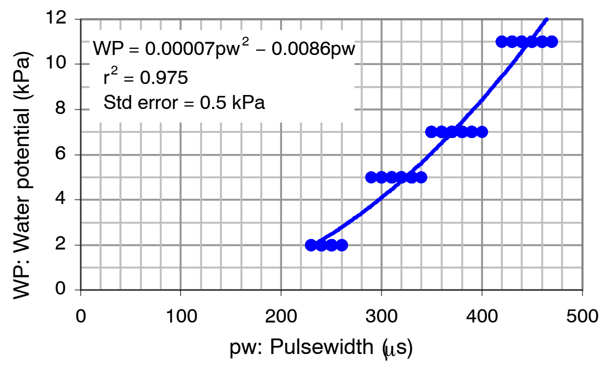

Figure 3. Calibration equation for 0- to 10-kPa range.

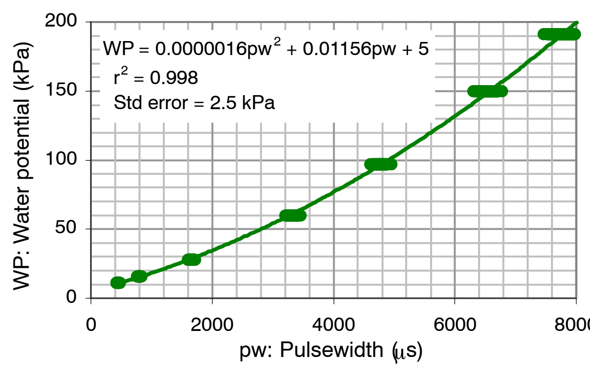

Figure 4. Calibration equation for 11- to 200-kPa range.

Table 2. Calibration resistor and microcontroller and meter values.

	Calibration Data						Calibration Equation		
		Microcontroller Circuit Pulsewidth					Microcontroller Circuit Water Potential		
	Fixed Resistor Value (Ω)	Average (µs)	Minimum (µs)	Maximum (µs)	Std Dev	Meter Water Potential (kPa)	Minimum (kPa)	Maximum (kPa)	Std Dev
Low range	676	250	240	260	6	2	2	2	0.2
(0-10 kPa)	825	320	310	330	8	5	3	5	0.3
	984	370	350	390	11	7	6	8	0.5
High Range	1192	450	430	460	12	11	9	11	0.6
(11-200 kPa)	2188	790	770	820	14	16	15	16	0.2
	4710	1650	1610	1700	26	28	28	30	0.4
	9950	3320	3220	3420	51	60	59	64	1.1
	14960	4760	4640	4900	72	97	92	101	1.9
	21830	6550	6360	6720	99	150	141	157	3.2
	27170	7770	7550	7970	121	191	180	201	4.4

For installation in the field, a wooden stake was driven into the soil at each moisture-sensor location. A plastic enclosure (Polycase, Avon, Ohio) was attached to the stake approximately 15 cm above the soil surface. A small hole was drilled in the bottom of the enclosure to allow sensor wires to be connected to the circuit board, and the circuit board was placed inside the enclosure. A desiccant pack was placed inside the enclosure to absorb moisture and protect the electronic circuitry.

Soil-moisture data were collected continuously throughout the 2004 and 2005 growing seasons. The microcontrollers were programmed to make and store sensor measurements at 2-h intervals. Periodically, at 1- to 2-week intervals, each moisture-sensor site was visited and data were downloaded from the circuit boards to a handheld computer. The handheld computer was then returned to the office and the data were transferred to a desktop computer for graphing and analysis.

An example of the moisture data collected with the datalogger is shown in figure 5. Data from three moisture sensors, installed at 15-, 30-, and 60-cm depths in a plot planted to corn, are plotted for the month of June 2005. Moisture-sensor measurements are shown in units of kiloPascals (kPa), with readings near 0 indicating very moist conditions and the moisture level decreasing as readings become more negative. Rainfall amounts recorded at a nearby weather station are shown, as are the times of irrigation events.

The moisture-sensor data were used to schedule irrigations of several plots in the same study. The goal was to prevent the average sensor value in each plot from decreasing below -60 kPa. When the average value of the three sensor measurements approached -60 kPa, an irrigation was scheduled. In some cases, a plot was irrigated slightly before reaching -60 kPa in order to accommodate the operation of the irrigation system and the scheduling of other field operations.

The performance of the circuit boards and calibration equations was evaluated by comparing circuit board readings with measurements made manually with a Watermark Meter. At several times during the 2004 and 2005 growing seasons, sensors at different locations in each field were disconnected from the circuit board, read with the meter, and then reconnected to the circuit board. A total of 111 manual measurements were collected, and the manual meter readings were plotted against the automated circuit board readings from the nearest time period. The results, shown in figure 6, indicate that the circuit board measurements correlated well with meter measurements, with a standard error of measurements similar to the original laboratory calibration. Absolute errors of the circuit board measurements ranged from 0 to ±9 kPa.

Problems encountered with the circuit boards deployed in the field fell into two categories: improper deployment and external damage. At several locations, the plastic enclosure containing the circuit board was installed too far to the side of the plant row, and was hit by a tractor during field cultivation operations. At a few other locations, the plastic enclosures were left laying on the soil surface rather than being attached to a wooden stake. A flooding rain caused the circuit

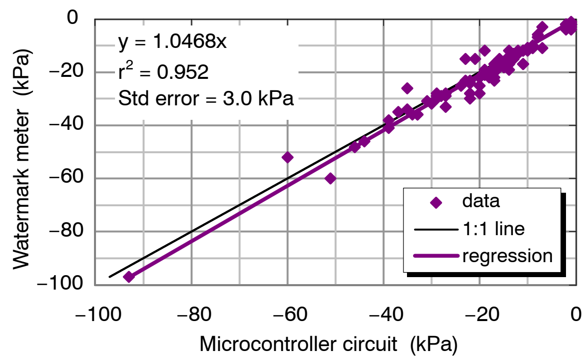

Figure 6. Manual meter readings compared with automated circuit measurements.

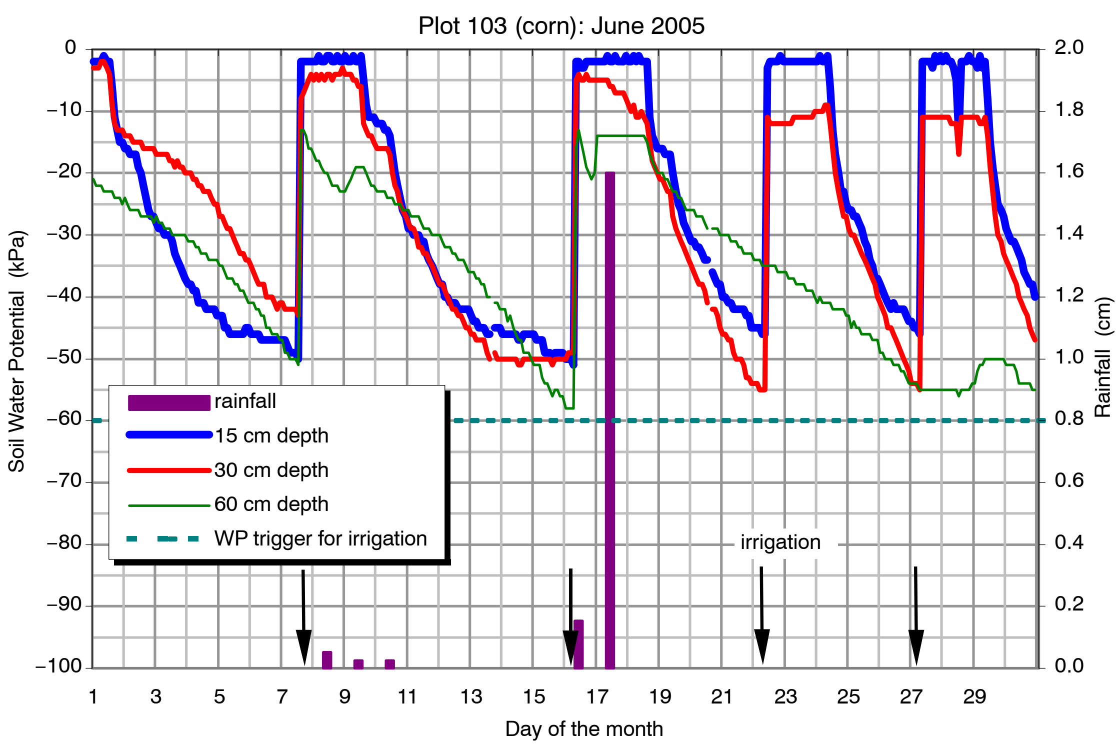

Figure 5. Example of data collected with moisture sensor datalogger.

boards and batteries to be damaged as water entered the plastic enclosures. Repeated damage, and complete disappearance of equipment occurred at several locations due to animal encounters.

Conclusion

A circuit was designed, and circuit boards were fabricated, to automate the collection of soil-moisture sensor data. The circuit was based on a programmable microcontroller to enable the construction of a simple and inexpensive device. Electronic components for timekeeping and long-term data storage, and a subcircuit for providing an alternating-current excitation required by the moisture sensor completed the circuit. The circuit boards required approximately US$20 in materials, and three hours of labor for fabrication. Circuit boards were deployed at 150 locations in various fields and used to collect moisture data for use in scheduling irrigations of corn, cotton, and soybean.

Microcontrollers are inexpensive and versatile devices, and are being used in increasing numbers in a variety of applications. Microcontroller-based circuits provide advantages over traditional electronic designs, including simpler designs with fewer components, by replacing hardware components with software functions. Microcontrollers have the potential to be applied in many agricultural applications to provide automation, data collection, and control capability to reduce labor requirements and increase the frequency of measurements and operations.

The availability of inexpensive, automated monitoring devices, such as the moisture-sensor datalogger discussed, may increase the adoption of moisture monitoring for use in scheduling irrigations. Where real-time scheduling of irrigations is not possible, the device could be used to monitor the irrigation practices in effect to gauge their performance. Through low-cost and low-labor requirements, more information can be collected more easily, making moisture monitoring and irrigation scheduling more attractive and feasible. A further, planned enhancement to the circuit, the addition of remote data collection via wireless communication, would provide the capability of real-time monitoring of field conditions and input for precision-irrigation systems.

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References

Cardenas-Lailhacar, B., M. D. Dukes, and G. L. Miller. 2005. Sensor-based control of irrigation in bermudagrass. ASAE Paper No. 052180. St. Joseph, Mich.: ASAE.

Cravotta, R. 2004. Field guide: 31st microprocessor directory. EDN, 5 August 2004.

Eldredge, E. P., C. C. Shock, and T. D. Stieber. 1993. Calibration of granular matrix sensors for irrigation management. *Agronomy* 85(6): 1228-1232.

Irrometer. 2002. Watermark soil moisture measurement installation and operation manual. Riverside, Calif.: Irrometer Co., Inc.

Leib, B. G., J. D. Jabro, and G. R. Matthews. 2003. Field evaluation and performance comparison of soil moisture sensors. *Soil Science* 168(6): 396-408.

McCann, I. R., D. C. Kincaid, and D. Wang. 1992. Operational characteristics of the Watermark model 200 soil water potential sensor for irrigation management. *Applied Engineering in Agriculture* 8(5): 603-609.

Migueletto de Andrade, M. 2003. Ptelnet. Ver. 0.6. Available at http://netpage.em.com.br/mmand/ptelnet.htm. Accessed 26 April 2006.

Rodrigues de Miranda, F. 2003. A site-specific irrigation control system. ASAE Paper No. 031129. St. Joseph, Mich.: ASAE.

Scanlon, B. R., B. J Andraski, and J. Bilskie. 2002. Miscellaneous methods for measuring matric or water potential. *Methods of Soil Analysis*, *part 4, Physical Methods*, eds. J. H. Dane and G. C. Topp, 643-670. Madison, Wis.: Soil Science Society of America, Inc.

Shock, C. C., J. Barnum, and M. Seddigh. 1998. Calibration of Watermark soil moisture sensors for irrigation management. *Irrigation Association, Proc. of the International Irrigation Show*, 139-146. Falls Church, Va.: Irrigation Association.

Shock, C. C., E. B. G. Feibert, L. D. Saunders, and E. P. Eldredge. 2002. *Automation of Subsurface Drip Irrigation for Crop Research.* St. Joseph, Mich.: ASAE.

Thomson, S. J., and C. F. Armstrong. 1987. Calibration of the Watermark model 200 soil moisture sensor. *Applied Engineering in Agriculture* 3(2): 186-189.

Thomson, S. J., T. Youmos, and K. Wood. 1996. Evaluation of calibration equations and application methods for the Watermark granular matrix soil moisture sensor. *Applied Engineering in Agriculture* 12(1): 99-103.

U.S. Bureau of Labor Statistics. 2004. National Compensation Survey: Occupational Wages in the United States, July 2004. Washington, D.C.: U.S. Department of Labor.

Yoder, R. E., D. L. Johnson, J. B. Wilkerson, and D. C. Yoder. 1998. Soilwater sensor performance. *Applied Engineering in Agriculture* 14(2): 121-133.